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STATIC ELECTRICITY IN THE APOLLO SPACECRAFT

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16. ABSTRACT Static electricity ignition hazards in the Apollo spacecraft were studied. Sparks with energies up to 2 millijoules can be generated by a space-suited man. This amount is sufficient to ignite flammable gas vapors and mists, but is not sufficient to ignite flammable solids such as logbook paper and cotton cloth present in the Apollo spacecraft. Biomedical sensors were used to ground the space-suited man to the spacecraft and eliminate static electricity ignition hazards. Temporary interference with cardiac readings from the biomedical sensors occurred during static charge drainage. This interference was minimized by adding a 0.1- to 1-megohm resistor in parallel to the ground circuit. Insulating fabrics used for the couch covers became electrified during use. The electrostatic charge on the couch covers was minimized by installing a grounded metal screen underneath the couch cover fabric. Storage lockers on the spacecraft floor and lithium hydroxide canisters stowed in the storage lockers were capable of accumulating several millijoules of electric energy before they were grounded to the spacecraft structure. No evidence existed of static electricity interference with the operation of the communications system of the portable life support system.			
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SUMMARY

Reports of electric sparks produced by static charges on the Apollo space suit prompted an investigation of static electricity ignition hazards and communications interferences in the Apollo spacecraft. The production of static electricity by contact of a space-suited man with the spacecraft was studied by rubbing the space-suited man with various materials and by measuring the voltage produced. Approximately 2 millijoules of electric energy was accumulated by the space-suited man; this amount is sufficient to ignite combustible gas vapors and mists. Static electricity ignition tests conducted on solid combustibles (logbook paper and cotton fabric) in the spacecraft showed that ignition of these solid materials by 2 millijoules of electric energy was unlikely. Biomedical sensors attached to the man's body and plugged into the spacecraft electronics provide an effective grounding path so that no danger of electrostatic charge buildup exists. However, static electricity drainage through the biomedical sensors temporarily interferes with cardiac measurements. This interference is minimized by adding a resistor in parallel to the ground circuit.

In addition to the space suit, other sources of static electricity were studied. The static electricity accumulated by the Teflon Velcro and the food bags did not present a problem. However, the Teflon-coated glass fiber couch cover and the various other Teflon-coated glass fiber cloth items (the constant-wear garment, tool bags, sleeping bags, and suit-stowage bags) became electrically charged while in use. Storage lockers on the command module floor are subject to frequent contact with insulating materials (such as sleeping bags), and the lockers were found to accumulate static electricity before they were grounded to the spacecraft structure. The lithium hydroxide canisters in the command module accumulated large static charges when removed from the storage lockers. Grounding of the canisters eliminated this effect.

Possible radio interference produced by static electricity in the communications system of the portable life support system was studied. Static charges were generated by rubbing a space-suited man with various materials. Transmissions from the portable life support system were monitored during the charging process and during spark discharge of the accumulated electricity. No radio interference existed.

INTRODUCTION

During the effort to remove all flammable materials from the Apollo spacecraft, combustible fabrics were replaced, whenever possible, with noncombustible glass fiber cloth. Following the replacement, previously unnoted static electricity effects occurred. For example, sparks were discharged during removal of equipment from the spacecraft wall, donning of suits, and installation of a glass-fiber-cloth-covered umbilical cable, which had previously been dragged across the command module (CM) floor.

These incidents of static electricity in the Apollo spacecraft prompted an investigation, since for several reasons, static electricity sparks are considered hazardous. The most obvious reason is the danger of a spark igniting combustible material in the spacecraft. Other hazardous effects of static electricity sparks are interference with communications or telemetered data and the involuntary reflex movements associated with discharge of a spark from a body. The objective of this investigation was to evaluate the static electricity ignition hazards resulting from electrostatic charges. This evaluation was accomplished by comparing the amount of electrical energy that was accumulated with the amount of energy required to ignite flammable materials in the spacecraft.

Electrostatic sparks are comparable to the sparks produced by capacitor discharges. When the electric field across the terminals of a charged capacitor exceeds the breakdown field of air, an electron avalanche takes place, producing a low-resistance path of ionized air, through which the electricity stored in the capacitor is quickly discharged. The property of the capacitor spark relevant to the static electricity ignition hazard is the spark energy. The minimum spark energy required for ignition of a gaseous combustible mixture is a definite, fixed quantity. Sparks with lower energy levels will not trigger ignition. Thus, to evaluate the static electricity ignition hazard of an electrostatic spark, the spark energy must be known. Because measurement of the energy actually released in a spark is difficult, a more practical procedure is to measure the energy which is available for spark formation and is stored in the capacitor. Under ideal conditions, all this stored energy may be discharged in the spark, but usually a small amount is dissipated in the electrical resistance which precedes the point of spark discharge. The energy E available is a function of the capacitance C and the voltage V , and E is equal to $0.5CV^2$. If the amount of stored energy is determined from capacity and voltage measurements and if the amount of stored energy is less than the minimum ignition energy, no hazard exists. If the amount of stored energy is larger than the minimum ignition energy, a hazard exists. This concept is the basis for evaluation of the static electricity ignition hazard.

Static electricity accumulation by the space-suited man was the major concern in the investigation of static electricity in the Apollo spacecraft. However, the entire spacecraft was surveyed to locate and evaluate other sources of electric charges. Static electricity interferences with communications and instrument readings were also studied. Sufficient spark ignition data for evaluation of the static electricity ignition hazard were not available; therefore, measurements were made of minimum spark ignition energy for typical flammable materials in the spacecraft.

Particularly helpful in this investigation was the work of Dale G. Sauers and Emilio Rodriguez, both of the Crew Systems Division, who provided the spark generator and the ignition chamber for spark ignition tests and who performed most of the tests. C. O. Cummings provided contractor assistance during most of the static electricity tests. Clyde Edmiston of the Space Electronics Systems Division organized the test involving the portable-life-support-system (PLSS) ground station and assisted in their performance and evaluation.

MINIMUM IGNITION ENERGY

The minimum ignition energy (MIE) has been extensively investigated for many combustible mixtures. For gaseous mixtures, the MIE is a definite quantity which depends on the type of fuel, on fuel concentration, and to a lesser extent, on the electrode configuration.

Representative values for gaseous mixtures are as follows (refs. 1 and 2): For hydrocarbon-air mixtures at 1 atmosphere, MIE values are in the range of 0.2 to 0.4 millijoule of spark energy. In a hydrocarbon-pure oxygen mixture at 1 atmosphere, MIE values range from 0.002 to 0.004 millijoule of spark energy. Lowering the pressure from 1 atmosphere to one-third atmosphere increases the MIE so that hydrocarbon-oxygen mixtures at one-third atmosphere have MIE values ranging from 0.02 to 0.04 millijoule of spark energy. (The Apollo spacecraft cabin atmosphere is pure oxygen at one-third atmosphere.) Hydrogen is the most easily ignited fuel, with MIE values 10 times less than the MIE values for hydrocarbons.

The energy required to ignite gas vapors or mists is not well defined because the spark energy must be divided in two parts; one part is used to evaporate the liquid fuel, and the other part is used to ignite the gaseous combustible mixture resulting from the evaporation. Generally, approximately 1 millijoule of spark energy is required for the ignition of fuel droplets in air (ref. 1). Fuel droplets in oxygen are expected to require less energy for ignition. The decrease is not expected to be a large one because much of the spark energy is used for fuel evaporation. Approximately the same amount of fuel must be evaporated in both air and oxygen because substitution of oxygen for air does not have a large effect on the lean flammability limit.

The energy required to ignite dusts or fibrous materials is poorly defined. A considerable amount of energy is required in order to vaporize a solid before ignition; therefore, 10 millijoules has been given (ref. 1) as an approximate energy requirement for ignition. Substitution of oxygen for air is expected to have little effect on this value. Because the MIE for solid materials is variable, measurement of the MIE for typical solid flammable materials present in the Apollo spacecraft was desirable.

MINIMUM IGNITION ENERGY FOR SOLID COMBUSTIBLES IN THE APOLLO SPACECRAFT

The Apollo spacecraft was surveyed for the presence of flammable materials on March 1, 1968. Logbook paper and cotton underwear were identified as the only easily flammable materials that would exist in the flight-qualified spacecraft. By passing capacitor sparks of known energy through the logbook paper and cotton underwear, their ignition characteristics were measured.

The spark ignition apparatus used for measuring the ignition characteristics of the logbook paper and cotton underwear is shown schematically in figure 1. The cloth or paper sample being tested was clamped loosely to a 1-inch-diameter copper disk electrode, which was electrically grounded to the metal chamber wall. A sharply pointed steel electrode was placed approximately 0.5 centimeter from the disk electrode. The pointed steel electrode passed from the chamber through a window, from which ignition was observed. The spark generator was calibrated by discharging sparks through a 100-megohm high-voltage resistor. Voltage across the resistor was measured as a function of time with an oscilloscope. The effective capacitance C of the circuit was calculated from the rate of decay of voltage across the 100-megohm resistor, and the actual voltage V available was considered to be the initial peak voltage. The spark energy E was calculated from the relation $E = 0.5CV^2$.

Measurements of the ignition characteristics of logbook paper and cotton underwear showed no defined ignition limit and the ignition appeared to be statistical. The following procedure was used to measure the ignition characteristics of the two materials. The spark generator was adjusted to give a spark of moderate energy. The spark was repeated until an ignition occurred or until 20 sparks had passed. If ignition occurred, the spark energy was decreased, and the procedure was repeated. If 20 sparks were passed without an ignition, the spark energy was increased, and the procedure was repeated. Prior to installation in the test chamber, the samples of cloth and paper were rubbed with sandpaper to generate as much lint as possible. Prior to starting the spark tests, the test chamber was evacuated to a pressure of less than 10 microns with the cloth or paper sample in place to remove all traces of moisture from the material. During the spark tests, a moderate flow of the test atmosphere was maintained throughout the chamber. For most of the tests, the disk electrode and pointed steel spark electrode were maintained approximately 5 millimeters apart. The distance between the two electrodes was varied in one series of tests with no apparent effect on the results.

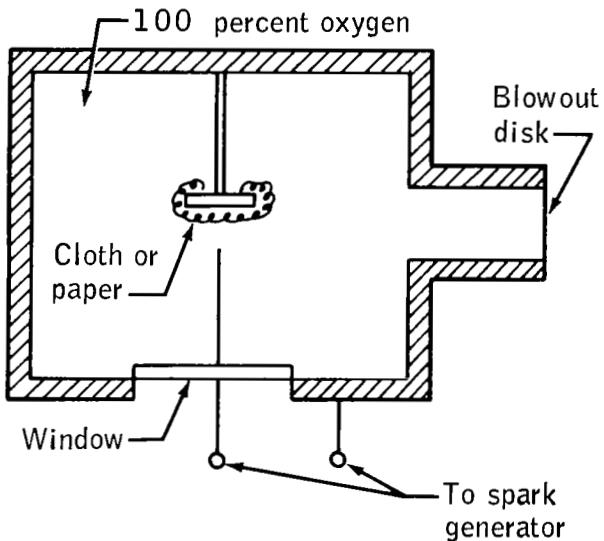


Figure 1. - Schematic diagram of spark ignition test chamber.

The results of the spark tests on the logbook paper are shown in table I, and the results of the test on the cotton fabric are shown in table II.

TABLE I. - SPARK IGNITION OF LOGBOOK PAPER
[16.5 psia oxygen]

Spark energy, mJ	Number of sparks	Results
20	20	No ignition
26	20	No ignition
32	20	No ignition
52	20	No ignition
74	20	No ignition
100	18	No ignition
120	10	1 ignition

The ignition of the logbook paper in a 16.5-psia, 100-percent-oxygen atmosphere was difficult. No ignitions occurred until 120-millijoule sparks were used. The sparks were observed to puncture the paper at all energies. To prevent a spark from passing through the hole made by the previous spark, the pointed electrode was moved after each spark.

The cotton fabric sample was ignited by sparks with energies as low as 9 millijoules in one test series, while 20 millijoules of spark energy were required in order to ignite the fabric in another test series. Change of the atmosphere from 16.5-psia pure oxygen to a 16.5-psia, 60-percent-oxygen, 40-percent-nitrogen mixture had little effect. Use of only 9 millijoules of spark energy yielded ignition in both atmospheres. However, a change of pressure from 16.5 to 6.2 psia in the pure-oxygen atmosphere had a pronounced effect. At the lower pressure, no ignition occurred up to energies of 170 millijoules. Higher energies were not available from the spark generator.

STATIC ELECTRIFICATION OF SPACE SUITS

The phenomenon of static electrification is familiar to almost everyone who has walked across a thick rug in a dry room and touched a grounded object. The basic

principles that underlie the static electrification effect and the means for eliminating the effect are less familiar. Because of the unfamiliarity of these basic principles, a general discussion of static electricity is given in the appendix.

TABLE II. - SPARK IGNITION OF COTTON CLOTH

Spark energy, mJ	Number of sparks	Results
16.5 psia oxygen, Feb. 29, 1968		
12	26	No ignition
20	21	1 ignition
26	28	No ignition
32	14	No ignition
41	21	No ignition
52	21	No ignition
74	5	1 ignition
16.5 psia oxygen, Mar. 6, 1968		
9	8	1 ignition
12	6	1 ignition
20	16	2 ignitions
6.2 psia oxygen, Mar. 6, 1968		
20	20	No ignition
32	20	No ignition
47	20	No ignition
100	20	No ignition
130	20	No ignition
150	21	No ignition
170	22	No ignition
16.5 psia total pressure: 10.0 psia oxygen, 6.5 psia nitrogen, Mar. 6, 1968		
9	10	1 ignition
12	10	1 ignition
20	10	2 ignitions
32	40	1 ignition
42	20	1 ignition
52	12	1 ignition
75	30	1 ignition
100	3	1 ignition

Capacitance Measurements

The objective of capacitance measurements is to determine where significant amounts of static electricity might accumulate on a space-suited man. To accomplish this objective, capacitance relative to the electrical ground was measured at different points. The results show (table III) that the most important point for charge accumulation is the body of the man inside the space suit. The observed body capacitance values of approximately 200 micromicrofarads are similar to values reported in reference 1.

TABLE III. - CAPACITANCE AT VARIOUS POINTS ON
STANDING MEN WEARING SPACE SUITS

Measuring point	Capacitance, $\mu\mu F$	
	Suit 1	Suit 2
Hand (glove removed)	200	185
Neck ring (blue part)	1	1
Neck ring (silver part)	36	26
Air exhaust fitting	2	1
Air inlet fitting	1	1
Zipper	54	66
Wrist ring	1	1
Wrist ring gage clamp	33	34
Pin through back flap of suit material	--	2

The inner lining of the space suit contains several alternating layers of metallized plastic. The capacitance of these layers relative to one another is large, but the capacitance of the layers relative to the electrical ground appears to be negligible. Contact with the metallized plastic layers was made by inserting a pin through the material on the back flap of the space suit. The result was surprising, because the capacitance of the metallized plastic layers relative to the electrical ground was expected to be at least as large as the body capacitance. A possible explanation is that the various pieces of metallized plastic sewn together to make the inner lining are not in electrical contact with one another.

Voltage Measurements

The electrostatic voltages, generated by contact of the space suit with various materials, were measured with an electrostatic voltmeter. To achieve electrical isolation for these tests, the space-suited man stood on an insulated plastic platform. Air hoses, communications links, and biomedical sensors were disconnected. The degree of electrical isolation for this configuration was tested by charging the space-suited man and measuring the electrostatic voltage generated by his suit as a function of time. The electrostatic voltage remained constant over periods of approximately 5 minutes,

which indicated that the electrical leakage resistance was more than 10^{12} ohms. Charging of the space-suited man was performed by a second man who rubbed the space suit with sheets of various materials.

In the first test series, the electrostatic voltage was measured at different points on the space-suited man after rubbing his suit with Beta 4190B glass fiber cloth. The electrostatic voltages measured at 30 percent relative humidity were as follows: space-suit arm, 4.3 kilovolts; arm ring, 3.4 kilovolts; neck ring, 2.2 kilovolts; and bare hand, 2.2 kilovolts. Repeated measurements of the same locations showed that the voltage differences that appeared to exist between various points on the space suit are the result of the method of measurement. After the space-suited man was charged by rubbing his suit with the glass fiber cloth, voltage was measured by touching a lead from the electrostatic voltmeter to the point of measurement. The voltmeter lead was then removed, and the voltmeter was discharged. Voltage was then measured at a different point. Invariably, the voltage was less in each succeeding measurement. The decrease in voltage was partially caused by leakage of the charge and partially by the 10-micromicrofarad capacitance of the voltmeter, which was discharged following each measurement.

A significant result of the voltage measurement on the space-suited man was the appearance of a charge on the man's body immediately after the charge had been generated on the surface of the space suit. Whether this charge was induced or whether electrical conductivity sufficient to redistribute the charge existed between the surface of the space suit and the man's body is uncertain.

To investigate the charge buildup on the space-suited man, the voltmeter was attached to his hand before the charge was generated on the space suit. Voltage was observed as a function of time after the space suit was charged. A qualitative representation of the charge buildup is shown in figure 2. An initial rapid decrease in voltage is followed by a small increase, which, in turn, is followed by a slower decrease to a steady value. In the steady condition, the suit surface and the man's body are observed to be at the same voltage. Possibly, the redistribution of charges throughout the man/space-suit combination is observed in this experiment.

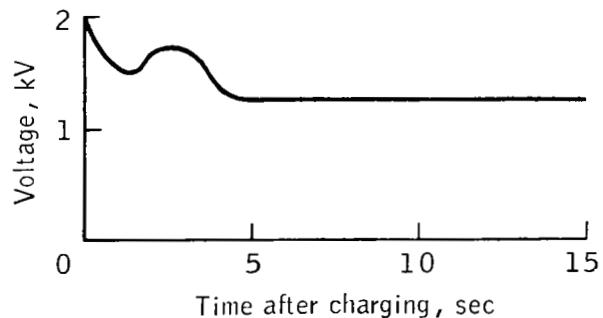


Figure 2. - Voltage on the body of space-suited man as a function of time after suit charging.

A second test series was run to determine the effect of contact material on the electrostatic voltage produced by rubbing the space suit. During these tests, voltages were lower (in the 1-kilovolt range) than voltages observed in the first test series (in the 2- to 4-kilovolt range). Either the high relative humidity (in the 50- to 60-percent range) during the second test series or the ionized air from the electronic equipment in the test room (or both) could have lowered the kilovolt range during this second test series. The results of this test shown in table IV, demonstrate that the Beta 4190B glass fiber cloth is the most favorable static electricity generator tested, while other materials yielded only approximately two-thirds as much voltage as the Beta 4190B glass fiber cloth.

The relative humidity has a significant effect on static electricity generation because of the effect of relative humidity on surface resistance as discussed in the appendix. During a third test series, the effect of relative humidity on static electricity generation was studied. The space-suited man was placed inside a wood chamber in which the humidity was controlled. Electrostatic charge was generated on the space-suited man by rubbing the suit with a Beta 4190B glass fiber cloth. The electrostatic voltage produced by the Beta 4190B glass fiber cloth was measured at the man's hand. The results in table V show that the electrostatic voltage increased as the humidity decreased. However, at the lowest relative humidity available (24 percent), the voltage was only 3.9 kilovolts. A value of 4.3 kilovolts was observed in an earlier test made at 30 percent relative humidity. At the 24-percent relative humidity level, the test subject developed 0.5 kilovolt of static electricity standing still and 3.0 kilovolts of static electricity by shuffling his feet.

TABLE IV. - STATIC VOLTAGE
PRODUCED ON SPACE-SUITED MAN
BY DIFFERENT MATERIALS

Material	Static voltage, kV
Glass fiber cloth:	
Beta 4190B	1.6
Beta 4484	.8
Teflon-coated glass fiber cloth:	
Armalon	1.0
Beta cloth	.3
T-162-42 TEF	1.0
Other:	
Blue nylon	1.0
Metallized mylar	0

TABLE V. - EFFECT OF RELATIVE
HUMIDITY ON
ELECTROSTATIC VOLTAGE

Relative humidity, percent	Maximum voltage, kV
69	2.4
50	3.0
24	3.9

EVALUATION OF IGNITION HAZARD FROM ELECTROSTATIC CHARGES ON A SPACE SUIT

The maximum capacitance in the man/space-suit system was found to be equal to the capacitance of the man's body, which is approximately 200 micromicrofarads. The maximum voltage observed under a wide range of conditions was 4.3 kilovolts. Therefore, the maximum electrical energy stored in the man's body was

$0.5(200 \times 10^{-12})(4.3 \times 10^3)^2$, or approximately 2 millijoules. Ignition of combustibles in the spacecraft require the following minimum amounts of energy. Ignition of gas vapors requires approximately 0.02 millijoule (at 0.33 atmosphere of pure oxygen); ignition of gas mists requires approximately 1 millijoule; and ignition of combustible solids requires 10 to 100 millijoules. A comparison of the spark energy available with the spark energy required for ignition indicates that electrostatic energy sufficient to ignite gas vapors and mists, but not sufficient to ignite solids, can accumulate on the space suit.

ELIMINATION OF ELECTROSTATIC CHARGES FROM THE SPACE SUIT

Although the accumulation of electrostatic charge does not present a hazard in the absence of combustible gas vapors and mists, accumulation of charges is undesirable. To make charge accumulation negligible, the body of the space-suited man must be electrically grounded to the spacecraft structure. As explained in the appendix and verified by a grounding test, even large resistances to the electrical ground (as high as 10^8 ohms) are acceptable.

The grounding test was performed in the following manner. One terminal of a 100-megohm resistor was electrically attached to the body of a space-suited man, while the other terminal was kept free. The space-suited man was then charged by rubbing his suit. After the electrostatic voltage became constant, the free terminal of the 100-megohm resistor was connected to the electrical ground. The voltage dropped to zero in less than 1 second. In a second grounding test, both terminals of the 100-megohm resistor were connected simultaneously (one to the space-suited man, the other to the electrical ground), and the suit was rubbed to generate static electricity. No electrostatic voltage was measured on the space-suited man.

Because the biomedical sensors are attached to the space-suited man's body, the sensors could possibly provide a grounding path. Earlier in the Apollo Program, a direct electrical connection from the astronaut's body to the spacecraft electrical ground had been provided, but the connection was removed to prevent possible electrical shocks. The circuits of the remaining biomedical sensors were examined to see if a grounding path existed. A section of the drawing of the electrocardiogram (ECG) assembly is illustrated in figure 3. Two ECG sensors are attached to the electrical ground circuit by two 22-megohm resistors wired in parallel. Thus, the ECG leads

provide an 11-megohm grounding path for static electricity from the space-suited man's body. Grounding tests showed that a 100-megohm grounding path was sufficient; therefore, no significant buildup of static electricity in the space-suited man should exist as long as the ECG leads are connected as illustrated in figure 3.

Since the current flow from the electrostatic-charge drainage usually ranges from 10^{-8} to 10^{-9} amperes (appendix) and since grounding resistance is approximately 10 megohms, voltages of 10 to 100 millivolts will appear on the ECG sensors. This voltage is similar in magnitude to the voltages normally measured by the ECG sensors. Consequently, interference with ECG readings of cardiac voltages was expected. This voltage interference was verified during crew compartment fit and function tests for SC 103 on July 17, 1968.

Two space-suited men were fitted with ECG sensors in the flight configuration. When one man rubbed his arm across the space suit of the other man, large temporary disturbances in the ECG readings were observed. Similar interferences will undoubtedly occur in flight.

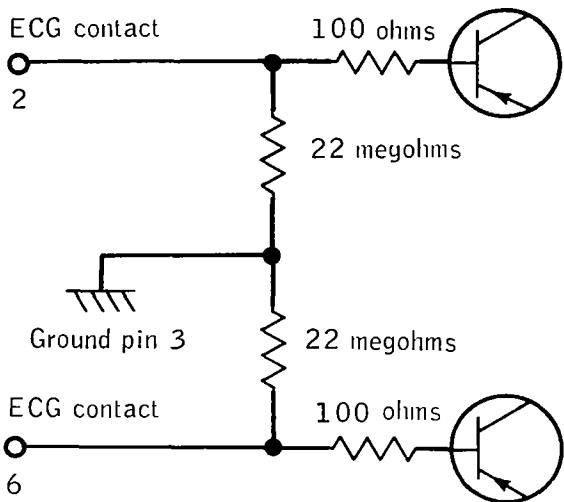


Figure 3. - Schematic section of ECG assembly electrical circuit in bioharness.

SURVEY OF THE APOLLO SPACECRAFT TO LOCATE OTHER SOURCES OF STATIC ELECTRICITY

The astronaut's space suit is only one of many insulating materials in the spacecraft which might generate static electricity by contact with metals or other insulators. The interior of the CM and the lunar module (LM) was studied to locate other sources of static electricity. A total of 200 square inches of Teflon Velcro is used in the LM, and 400 square inches of Velcro is used in the CM. The Velcro is used for stowage of as many as 600 items. Temporary stowage operations will probably require 20 000 separations of Velcro-attached items, in groups of 100 to 200 operations. In part of the LM restraint system, the floor of the crew compartment has several Velcro strips 28 inches long and 1-1/2 inches wide. Velcro is also used on the CM floor and on the bottom of the astronauts' boots. Electrostatic voltage tests verify that no hazard is expected from the use of Velcro in the spacecraft. Both elements of the Velcro are Teflon; therefore, little or no static electricity generation is expected from separation of the meshed Velcro (appendix).

The food bags and plastic storage container used in the spacecraft are composed of different materials; therefore, removal of the food bags from the storage container generates static electricity. However, electrostatic charges on the food bag drain to the space-suited man's hand and, subsequently, to the spacecraft ground either through

the biomedical sensors or through physical contact with the spacecraft wall. Electrostatic charges on the plastic storage container drain to the spacecraft ground, since the container is in physical contact with the spacecraft. Consequently, use of the food bags and the storage container in the spacecraft does not present a problem.

As the astronauts move on and off the couches, contact of the space suit or constant-wear garment with the plastic couch cover generates static electricity. The charged couch cover may then induce electrostatic charges in a nearby object.

The constant-wear garment, suit-stowage bags, tool bags, and sleeping bags are made from Teflon-coated glass fiber cloth. Contact of the constant-wear garment with the metal parts of the spacecraft generates static electricity, which accumulates in the body of the man wearing the garment. In the flight configuration, the man is barehanded so that he discharges himself of electrostatic charges each time the metal parts of the spacecraft are touched. If the man does not touch the spacecraft for a long period of time, an appreciable electrostatic charge may accumulate and may produce a spark when the wall is touched. Removal of a tool from the tool bags generates static electricity which accumulates in the body of the man holding the tool, if he is not grounded to the spacecraft structure.

The stowage of constant-wear garments, sleeping bags, and lithium hydroxide canisters in the storage lockers on the floor of the CM generates static electricity. These storage lockers are made of anodized aluminum and are held in place by latches so that they may be removed from the spacecraft. A metal locker placed 0.005 inch from the spacecraft wall has a capacitance of 6400 picofarads per square foot of locker surface. Charging this capacitance to 4 kilovolts results in the storage of approximately $50 \text{ mJ}/\text{ft}^2$, which is a hazardous quantity of electrostatic charge. Whether or not an electrostatic charge of this size can accumulate in the storage lockers depends on how completely the storage lockers are electrically isolated from the spacecraft metal structure. To determine the degree of electrical isolation of the storage lockers from the spacecraft structure, measurements on the resistance to the electrical ground of the storage lockers on SC 103 for the Apollo 8 mission were performed. (The results are shown in table VI.) Three storage lockers were electrically isolated from the spacecraft, and two storage lockers were grounded to the spacecraft structure. The results confirm that a dangerous accumulation of electrostatic charge in the storage lockers is possible unless the lockers are electrically grounded. Some of the storage lockers are used to hold lithium hydroxide canisters, which are held in place by an insulating liner in the locker. Insertion and removal of the canisters from the insulated storage locker generate static electricity in the locker and in the canister.

Static electricity is also produced by moving belts. A glass fiber belt was to be used to hoist samples of lunar material from the lunar surface into the LM. This moving belt was expected to produce static electricity.

Flowing insulating liquids generate static electricity. An ethylene glycol-water mixture is pumped through the cooling loops. However, this fluid is moderately conductive, and the cooling loops (except the plastic tubing in the space suit) are metallic and are grounded. Because of the low conductivity of the ethylene glycol-water mixture, no static electricity generation is expected from the fluid. Similar considerations apply to the liquid electrolytes in the fuel cell.

TABLE VI. - RESISTANCE TO ELECTRICAL GROUND CIRCUIT OF
EQUIPMENT STORAGE LOCKERS IN SC 103^a

Equipment locker	Resistance, MΩ
A2	>10
A3	<. 1
A6	<. 1
A7	>10
A8	>10
B5	<. 1
B6	<. 1

^aJuly 17, 1968.

DISCOVERY AND REMOVAL OF STATIC ELECTRICITY HAZARDS FROM SOURCES OTHER THAN THE SPACE SUIT

Many sources of static electricity other than the space suit exist in the spacecraft. The relative importance of these sources can be determined only in operational tests, in which men occupy the spacecraft and simulate the tasks to be performed in flight. During the simulations, four effects of static electricity were observed by the crewmen; three of which were considered potentially hazardous. The spacecraft was modified to eliminate each hazard.

The first effect of static electricity occurred when the surface of the space-suit glove was charged by handling various objects. When the charged glove touched the face of a CM gage, the gage reading was altered by the electrostatic charge. However, this electrostatic charge effect presented no hazard and was disregarded.

The first electrostatic effect considered to be hazardous was produced by the plastic couch cover. Voltages up to 10 000 volts were observed on the couch cover after use of the couch by the crewmen. Furthermore, the voltage appeared to leak off the couch cover very slowly. While there was no danger of sparks directly from the couch cover (because of its insulating nature), a real danger of induced voltages in conducting objects such as space-suited men and tools that moved into the vicinity of the charged couch cover existed. Such induced voltages in conducting objects could produce dangerous sparks. The effects of these induced voltages were noted by crewmen who observed their body hair standing up when they lay on the couch.

Two methods were studied to eliminate the electrostatic charge generated by the couch cover. First, commercial antistatic coatings were applied to the couch cover material. This method proved ineffective because the coatings would not stick to the Teflon-coated material. A second method was to shorten the electrical path to the spacecraft electrical ground to increase the rate of electrical discharge of the couch cover material. Elimination of the electrostatic charge generated by the couch cover was accomplished by installing a grounded metal screen underneath the couch cover. This method proved effective in reducing voltages to less than 100 volts.

A second potentially hazardous situation became evident during SC 103 simulated altitude test runs. When lithium hydroxide canisters were withdrawn from the storage lockers, electric sparks were seen and heard by the crewmen. The sparks were observed to jump from the canister to the storage locker at the instant of withdrawal. Laboratory tests were performed to determine the amount of energy in the sparks. Storage lockers from SC 103 and lithium hydroxide canisters from both SC 101 (Apollo 6) and SC 103 were used for these tests. The lithium hydroxide canisters from the two spacecraft had similar outer dimensions and internal construction, but the outer canister wall of the SC 101 canisters was made of stainless steel and the outer wall of the SC 103 canisters was made of Teflon-coated aluminum. To hold the lithium hydroxide canisters snugly in place, the storage lockers were lined internally with pads of Teflon and silicone rubber. When the canisters were pushed into the storage locker, the pads compressed to make the canisters fit securely. These pads provided nearly complete electrical insulation between the canister and the locker. Measurements showed the resistance between the lithium hydroxide canister and the storage locker to be greater than 10 000 megohms.

Voltages and capacitances for the lithium hydroxide canister relative to the storage locker were measured for a standard test configuration. The canister was installed in the locker, momentarily grounded, and then rapidly withdrawn to a position where the canister bottom was about one-half inch from the locker top. This configuration corresponded approximately to the configuration in which sparking occurred. The spark jumped from the bottom of the canister to the top of the locker as the canister came completely out of the locker.

The capacitance of the lithium hydroxide canister relative to the storage locker was approximately 30 picofarads in the test configuration, and the voltage was approximately 10 000 volts. These values were approximately the same for all storage lockers tested; the values corresponded to a theoretical spark energy of approximately 1.5 millijoules. The theoretical spark energy is sufficient to ignite gas vapors or mists, but it is not sufficient to ignite solid combustibles. Elimination of the canister/storage lockers spark source was considered necessary, and elimination was accomplished by grounding the lithium hydroxide canisters during insertion and withdrawal. The canisters in the LM and in the PLSS were also tested. No static electricity charges were found in these two articles because of the absence of an insulating liner inside the storage lockers.

During simulation of lunar surface activities, a third potentially hazardous static electricity effect was found. The lunar sample receiving containers are hoisted into the LM by means of a Teflon fabric belt and metallic pulley combination. It was found that the hoisting operation electrically charged the belt to approximately 5000 volts. The charged belt produced strong attractive forces in powdered minerals (hematite

and basalt). When the charged belt was placed 1 inch above a tray of powdered mineral, a substantial quantity of powder flew vertically upward and stuck to the belt. This alerted investigators that the belt might carry the lunar dust (which could be either toxic or flammable) into the LM along with the lunar sample container. To prevent this, the belt was sewn in a zigzag pattern with metal thread. The conducting metal thread effectively reduced the electrical charge to only a few hundred volts and completely eliminated dust pickup due to electrostatic charge.

COMMUNICATIONS INTERFERENCE FROM STATIC ELECTRICITY

A communications receiver was monitored during static electricity tests in the controlled humidity chamber where a space-suited man was rubbed with sheets of insulating material. Moderate radio static was observed during electrification of the space suit by contact with a glass fiber cloth. Strenuous exercise of the space-suited man also produced radio static, but static was not as great as the radio static produced by rubbing the space suit with a glass fiber cloth. Static interference with radio transmission was observed during several vacuum chamber tests of the PLSS. As a result of these tests, possible communications interference from static electricity appear to exist.

To evaluate this possibility, a static electricity test was performed with a space-suited man wearing the PLSS in the flight configuration. The space-suited man, fully instrumented with biomedical sensors, was placed inside a controlled-humidity anechoic chamber, and the relative humidity below 10 percent was maintained. A receiving station was placed outside the chamber to receive telemetered data from the PLSS. Antennas for the receiving station were installed inside the chamber. Seven biomedical channels, a voice channel, and the radio-frequency signal strength were monitored by the receiving station.

During the static electricity tests, the space-suited man was isolated from the electrical ground. Approximately 2 kilivolts were generated by rubbing the space suit with a glass fiber cloth, during which time all information channels of the receiving station were monitored. The channels were again monitored when the space-suited man was grounded. Static electricity generation and discharge produced no communications interference in any biomedical or voice channel or in the radio-frequency signal strength. Therefore, static electricity generation and discharge does not produce undesirable communications interference with information transmission from the PLSS.

CONCLUSIONS

The amount of static electricity that can be accumulated by a space-suited man, who is electrically isolated, is sufficient to ignite combustible gas vapors and mists but is not sufficient to ignite combustible solids found in the Apollo spacecraft. Connection of the biomedical sensors to the space-suited man provides a grounding path sufficient to prevent appreciable charge buildup. Consequently, no hazard exists when the biomedical sensors are connected to the space-suited man. Temporary interference with biomedical sensor readings occurs during static-charge drainage. This

interference can be minimized by providing a 0.1- to 1.0-megohm path parallel to the ground circuit. (A complete short circuit to the ground would be more suitable, but it cannot be used because of an electric shock hazard.)

Other static electricity ignition hazards were discovered during operational tests of the spacecraft. These hazards included a highly charged plastic couch cover, spark discharges from lithium hydroxide canisters, and poorly grounded storage lockers. The couch cover hazard was eliminated by installing a grounded metal screen underneath the couch cover. The lithium hydroxide canister hazard and the storage locker hazard were eliminated by proper grounding.

Static electricity interference with transmission of data and voice from the portable life support system was studied; however, no interference was discovered.

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APPENDIX

BASIC PRINCIPLES OF STATIC ELECTRICITY GENERATION AND PREVENTION

Generation of Static Charges

The free energy of a valence electron depends upon the material in which it is located. Consequently, when two different materials are brought in contact with one another, a free energy difference initially exists at the boundary. Impelled by this energy difference, electrons flow across the boundary from one material to the other, until the energy difference is neutralized. As a result of the transfer of electrons, a potential difference, called the contact potential, appears. The contact potential is a small voltage, usually from approximately 1 to 100 millivolts.

When the two materials are separated, the transferred electrons tend to flow back to their original places. If the two materials are good electrical conductors, electron mobility is high, and the flow is extremely rapid. Because of the rapid flow, separation of conducting materials without the return flow occurring is not possible, and little or no static electricity is generated when conducting materials are separated. However, for insulators, electron mobility is low, and the return flow is relatively slow. Because of the slow return flow, some of the charge may be trapped by separating the insulator quickly from the other material. Thus, contact and separation will generate static electrical charges when an insulator and a metal or two insulators are involved, but static electrical charges are not generated if two metals are involved.

Static charges produced by contact and separation may be more than 10 000 volts. How this large a voltage can result from the small contact potential can be explained by considering the properties of a capacitor.

The voltage V of a capacitor is directly proportional to the charge stored in it Q and inversely proportional to the capacitance C .

$$V = Q/C \quad (A1)$$

The capacitance of two parallel conducting flat plates is inversely proportional to the distance t between the plates.

$$C = K/t \quad (A2)$$

where K is a proportionality constant. Combining equations (A1) and (A2), the voltage on a capacitor is related to the spacing of the plates by

$$V = Qt/K \quad (A3)$$

When the charge Q is held constant, the voltage is directly proportional to the spacing of the capacitor plates.

Returning to the generation of static electricity by contact, consider the two different materials in contact to be the two plates of a capacitor. When they are in contact, the spacing cannot be less than an atomic diameter because of repulsive forces that appear at close atomic spacings. This distance is about 1 angstrom or 10^{-8} centimeters. In this contact configuration, electrons are transferred from one material to the other, as described previously. When the materials are separated, some of the transferred electrons are trapped, assuming no external leakage path exists for the transferred electrons to return to the material they were part of originally. Since the number of transferred electrons remains constant after separation, the charge Q of the capacitor remains constant as the plates of the capacitor are separated.

Assume that the initial contact potential is 1 millivolt. When the two materials are separated from 10^{-8} to 10^{-5} centimeters, the voltage also increases 1 volt (as shown by eq. (A3)). Note that the plates are still only 0.01 millimeter apart. If the materials are moved 1 centimeter apart, the voltage would theoretically become 100 000 volts. However, in reality, corona discharge occurs before a potential this high can be reached and, thus, limits the voltage. The largest electrostatic voltages generated under ordinary conditions are about 30 000 volts. More commonly, voltages of 1000 to 5000 volts are found.

In summary, generation of electrostatic charges may be expected whenever an insulator and a metal or two insulators contact each other and are separated (refs. 1, 3, and 4). Friction is unnecessary; simple contact is sufficient. Voltages in the range of 1000 to 10 000 volts are produced under usual conditions.

Elimination of Static Charges

Large accumulations of electric charge with high potentials which may lead to dangerous sparks require metallic conductors. Sparks from highly charged insulators are normally feeble, since the internal resistance of the insulator prevents the rapid flow of electrons required to maintain an energetic spark. Thus, in searching for static electricity ignition hazards, all metallic surfaces at which charge generation may be occurring, or any surface on which charges generated elsewhere may accumulate are examined. These surfaces must be connected electrically (grounded) to eliminate the possibility of electrical spark discharges. The amount of grounding required to eliminate the accumulation of static electricity in metallic conductors is not large, as seen from the following considerations.

Figure 4 shows schematically a metallic charge conductor connected to the ground circuit by a leakage resistance R . The capacitance C of the conductor is measured relative to the electrical ground. If static electricity is assumed to flow into the conductor with a current of I , the charge Q will build up with time t according to the law

$$Q = IRC \left[1 - \exp\left(\frac{-t}{RC}\right) \right] \quad (A4)$$

At equilibrium, when $t = \infty$

$$Q = IRC \quad (A5)$$

Since, for a capacitor, $V = Q/C$, then

$$V = IR \quad (A6)$$

The maximum voltage is determined by Ohm's law, in which the current is the charging current and the resistance is the leakage resistance. Experimentally, static electricity charging currents were seldom found to exceed 10^{-8} amperes. For leakage resistance of 10^9 ohms or less, the maximum electrostatic charge will be 10 volts or less. The minimum sparking voltage in air is sometimes given as 350 volts. Thus, very high resistances are shown to be sufficient to conduct static electricity to the electrical ground because of the slow generation of electrostatic charge by the usual processes of static electrification. Leakage resistances of 10^{11} ohms or greater allow the generation of voltages in amounts more than 1000 volts.

Constant static electricity currents are generally produced by rotating machinery or flowing liquids. The intermittent generation of charge by occasional, accidental contact of two materials is also common. In the situation of charge generation by accidental contact of two materials, consideration of the leakage of charge from the conductor charged by an amount Q_0 is helpful. The charge decays exponentially with time, according to the equation

$$Q = Q_0 \exp\left(\frac{-t}{RC}\right) \quad (A7)$$

where t is the time after charge generation has stopped. Since the capacitance does not change with time, capacitance is equivalent to

$$V = V_0 \exp\left(\frac{-t}{RC}\right) \quad (A8)$$

The static voltage will decay exponentially with time, with a time constant RC . Typical values of capacitance are 100 to 400 micromicrofarads for a human being, 500 micromicrofarads for an automobile, and approximately 1000 micromicrofarads for a tank truck. Thus, capacitances in the 100- to 1000-micromicrofarad range are commonly encountered. (Special situations may yield much higher values.) Maintenance of a voltage decay time constant less than 0.1 second, which corresponds to maximum leakage resistances in the 10^8 - to 10^9 -ohm range, is desirable. For leakage resistances more than 10^{11} ohms, the decay times are more than 10 seconds. Thus, the accumulation of static electricity in metallic materials may be easily eliminated by electrically connecting the material to the ground circuit. Because of the small currents involved, large resistances of 10^8 ohms or 100 megohms provide an effective grounding path (refs. 1, 3, and 4).

Consider static electrification of insulators, which always occurs in contact generation of static electricity. Accumulation of static electricity is considered less hazardous in insulators than in metallic conductors, because the high resistance of an insulator prevents the production of energetic sparks except in extreme cases. However, electrified insulators can induce charges in other objects, which can, in turn, produce undesirable effects. Sizable charges may be produced when metallic conductors are brought close to the charged insulator. To produce hazardous voltages in metallic objects by induction, a particular sequence must be followed (fig. 5).

In diagram A of figure 5, the charged insulator is separated a considerable distance from the uncharged metallic conductor. Diagram B shows the two have been moved together. The charge on the insulator induces a separation of charge on the conductor. In diagram C, the conductor is grounded. Upon grounding of the conductor, the induced charges separate farther apart with electrons moving down the ground lead to the electrical ground. The charge (in diagram D) is trapped on the conductor by breaking the ground connection and by moving the conductor away. The charge on the insulator remains unchanged, allowing the process to be repeated indefinitely.

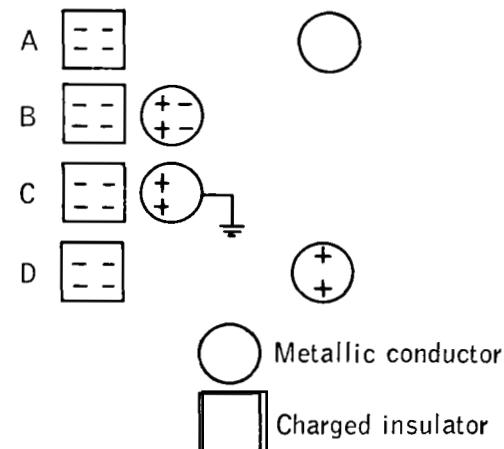


Figure 5. - Charging a metallic conductor by induction from a charged insulator.

The induced charge from electrified insulators also produces forces of attraction between the conductor and the charged insulation (fig. 5, diagram B). As a result of this attraction, dust particles adhere tightly to electrified insulators. Dust particles of insulating material may be electrified, and the particles will either adhere to the electrified surface tightly (if the particles are of the opposite charge) or be repelled by the electrified surface (if the particles are of the same charge).

Elimination of static electricity from insulators is difficult. Grounding with a point-contact is ineffective because the high resistance of the material prevents charge drainage. One effective method of controlling static electricity in insulators is to coat the surface of the insulator with a layer of conducting material and to ground the surface layer. The surface layer of conducting material may be very thin, but it has two useful effects. One effect is that fewer electrons are trapped in the contact-separation process, so that less voltage is generated. Another useful effect of the surface layer is that the large area of electrical contact allows charge drainage from the insulator with greater effectiveness than a point-contact would allow. In many situations, the voltages generated by contact and separation are reduced by the conducting surface layer making grounding of the layer unnecessary.

The conducting surface layer may be produced by several methods. The most common method is to use adsorbed moisture. The surface resistance of an insulator is extremely sensitive to the relative humidity, which controls the amount of water adsorbed on the surface. A 10-percent change in relative humidity may change the surface resistance by several orders of magnitude. Maintaining a film of adsorbed water under low-humidity conditions can be facilitated by coating the surface with a hygroscopic material. Commercial antistatic agents are based on this coating principle. The antistatic agent is composed of a liquid detergent to wet the surface and glycerine (or a similar hygroscopic material) to maintain a water film on the wet surface. Materials such as Teflon, which cannot be wet, require a different method to obtain a surface layer conductor; one method is to cover the surface with a grounded metal screen.